

Mid-Oceanic ridge system

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The global mid-ocean ridge system is the largest single volcanic feature on the Earth, encircling it. The Earth's crust is spreading, creating new ocean floor and literally renewing the surface of our planet. Older crust is recycled back into the mantle elsewhere on the globe, typically where plates collide. The mid-ocean ridge consists of thousands of individual volcanoes or volcanic ridge segments which periodically erupt.

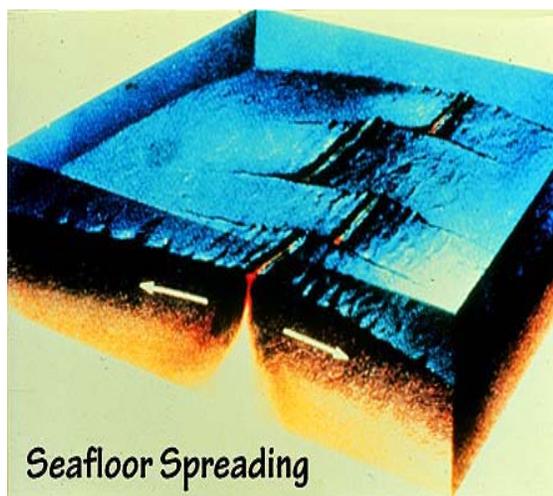
Beneath a typical mid-ocean ridge, mantle material partially melts as it rises in response to reduced pressure. This melted rock, or "magma", may collect in a reservoir a few kilometers below the seafloor, awaiting eruption. Much of the magma eventually freezes in a place within the crust, forming the bulk of the new oceanic crust without erupting at all. Average oceanic crust is about 10km thick, but only the upper 1 to 3 km is formed by eruption processes. When magma pressure builds up enough to force its way out to the seafloor, eruption occurs. "Dikes" are magma-filled cracks and are the conduits that magmas flow through to reach the surface. A typical ridge eruption leaves behind a dike that is 10s of centimeters up to 2 meters in width, extending between the crustal magma chamber and the eruptive fissure at the surface. Lavas pour from the fissure across the surface of the volcanic seafloor, adding a thin coat of new lava (typically <10 m thick) with each eruption. This process of magma ascending and lavas erupting is on-going and perpetual.

Because the ridge is the site of focused volcanic activity, seawater circulates actively to cool the new crust. This heated water reacts with the volcanic rock, dissolving out metals and depositing them around seafloor hot springs. Within the volcanic upper crust, subterranean chambers and fractures filled with heated water act as incubators for microbes that live in some of the harshest conditions ever discovered to support life. These microbes are the foundation for a rich ecosystem that thrives only at these hydrothermal vents.

Seafloor spreading

Our Earth is a warm planet sailing through cold space. Much of the rocky interior (the mantle) of our planet is hot enough to flow as molten magma through the weak zones at ridge axes. The surface of the Earth, however, is chilled by the cold of space, and so the familiar rocks of the

Earth's surface are hard and brittle. The cold outer layer of our planet, which holds together as a rigid shell, is not made of one solid piece. Instead this shell is broken into many separate pieces, or tectonic plates, that slide around atop the mobile interior.



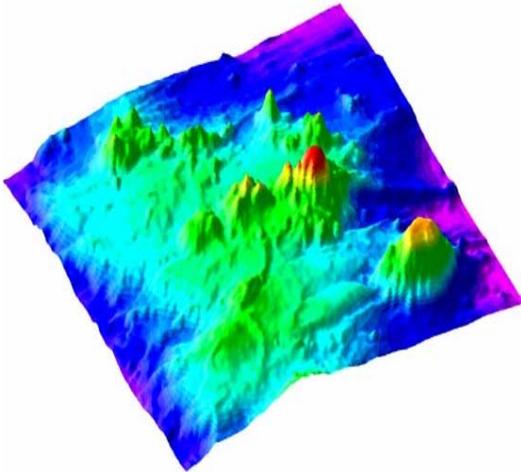
The tectonic plates are in motion. They are driven by the flowing mantle below and their motions are controlled by a complex puzzle of plate collisions around the globe. There are three types of plate-plate interactions based upon relative motion: *convergent*, where plates collide, *divergent*, where plates separate, and *transform* motion, where plates simply slide past each other. *Seafloor Spreading* is the usual process at work at divergent plate boundaries, leading to the creation of new ocean floor. As two tectonic plates slowly separate, molten material rises up from within the mantle to fill the opening. Thus the rugged volcanic landscape of a mid-ocean ridge is created along the plate boundary.

Seamounts and hot spots

Seamounts are individual volcanoes on the ocean floor. They are distinct from the plate-boundary volcanic system of the mid-ocean ridges, because seamounts tend to be circular or conical. A circular collapse caldera is often centered at the summit, evidence of a magma chamber within the volcano. Large seamounts are often fed by "hot spots" in the deep mantle. These hot spots are associated with plumes of molten rock rising from the deep within the

Earth's mantle. These hot spot plumes melt through the overlying tectonic plate and supply magma to seamounts.

Hot spot plumes are long lived. Therefore, as a moving tectonic plate passes over a mantle hot spot, a chain of volcanoes is produced with a systematic age progression - from older to younger. The Laccadive and Maldives islands and Hawaiian Islands, the Galapagos Islands, the Azores, and the Cobb-Eikelberg chain that includes Axial volcano are all examples of hot spot chains. When a hot spot interacts with a mid-ocean ridge, the affected ridge segments tend to receive a greater-than-normal supply of magma from the mantle, leading to more frequent eruptions, and formation of volcanic edifices right on the ridge. Iceland and Axial Seamount are both examples of a hot spot located on the axis of a mid-ocean ridge. The Afanasy Nikitin Seamount in the Indian Ocean reconstructed from multibeam bathymetry is shown below.



Subduction Zones / Convergent plate boundaries

The nature of a convergent boundary depends on the type of lithosphere in the plates that are colliding. Where a dense oceanic plate collides with a less-dense continental plate, the oceanic plate is typically thrust underneath because of the greater buoyancy of the continental lithosphere, forming a subduction zone. At the surface, the topographic expression is commonly an oceanic trench on the ocean side and a mountain range on the continental side. An example of a continental-oceanic subduction zone is the area along the western coast of South America where the oceanic Nazca Plate is being subducted beneath the continental South American Plate.

Oceanic / Continental

It is believed that as the subducting plate descends, its temperature rises driving off volatiles (most importantly water) encased in the porous oceanic crust. As this water rises into the mantle of the overriding plate, it lowers the melting temperature of surrounding mantle, producing melts (magma) with large amounts of dissolved gases. These melts rise to the surface and are the source of some of the most explosive volcanism on Earth because of their high volumes of extremely pressurized gases (consider Mount St. Helens). The melts rise to the surface and cool forming long chains of volcanoes inland from the continental shelf and parallel to it. The continental spine of western South America is dense with this type of volcanic mountain building from the subduction of the Nazca plate. In North America the Cascade mountain range, extending north from California's Sierra Nevada, is also of this type. Such volcanoes are characterized by alternating periods of quiet and episodic eruptions that start with explosive gas expulsion with fine particles of glassy volcanic ash and spongy cinders, followed by a rebuilding phase with hot magma. The entire Pacific Ocean boundary is surrounded by long stretches of volcanoes and is known collectively as *The Ring of Fire*.

Continental / Continental

Where two continental plates collide the plates either buckle and compress or one plate delves under or (in some cases) overrides the other. Either action will create extensive mountain ranges. The most dramatic effect seen is where the northern margin of the Indian Plate is being thrust under a portion of the Eurasian plate, lifting it and creating the Himalayas and the Tibetan Plateau beyond. It has also caused parts of the Asian continent to deform westward and eastward on either side of the collision.

Oceanic / Oceanic

When two plates with oceanic crust converge they typically create an island arc as one plate is subducted below the other. The arc is formed from volcanoes which erupt through the overriding plate as the descending plate melts below it. The arc shape occurs because of the spherical surface of the earth (nick the peel of an orange with a knife and note the arc formed by the straight-edge of the knife). A deep undersea trench is located in front of such arcs where the descending slab dips downward. Good examples of this type of plate convergence would be Japan and the Aleutian Islands in Alaska.

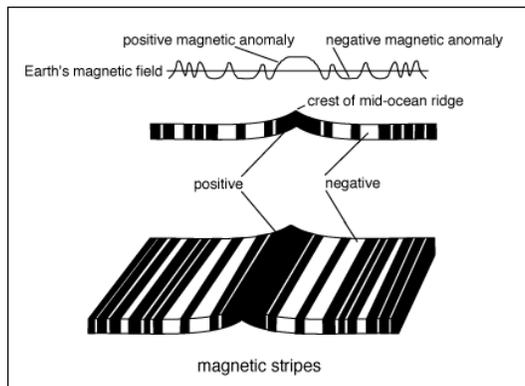


Magnetic anomalies over ridge axis

In order to understand how magnetic stripe anomalies support plate tectonics we need to understand (1) the basics of plate tectonic theory, especially the part about sea-floor spreading; (2) how the Earth's magnetic field behaves, and (3) how magnetic stripe anomalies are formed and interpreted. The important point is that the oceanic crust is composed of high density rocks rich in iron (mainly a coarse-grained igneous rock called gabbro, but also dolerite and basalt, which have the same composition as gabbro are finer grained). Gabbro, dolerite and basalt are formed by melting of the rock peridotite at mid-ocean ridges which forms the underlying mantle. Peridotite is rich in minerals that contain iron, so the magma and ultimately the gabbro, dolerite and basalt derived from it are also rich in iron-bearing minerals.

magnetic field is a continuous, but variable, process that causes change in not only the intensity of the magnetic field, but also causes the Magnetic North Pole to move as well as the reversal of the earth's entire magnetic field.

When lava hardens into rock, containing grains of iron oxides that point toward the magnetic pole as the rock solidifies. Thus, these grains are permanent records of the location of the earth's magnetic field. As new crust is created on the ocean floor, the new crust solidifies, with its iron oxide acting like miniature compass needles. The magnetic bands have been matched on either side of the mid-oceanic ridge out to the edges of the ocean to determine the distance between continents on either side of the ridge. Magnetic reversals helped to prove the theory of plate tectonics and continental drift.



The earth's magnetic field has reversed approximately 170 times over the last 100 million years. The intensity of the magnetic field has been decreasing over time since it has been measured and some scientists expect that at the current rate of decline, there may be another magnetic reversal in approximately 2000 years. That should be enough time to replace all of our compasses.

The Earth's magnetic field.

In the 1950s, ocean-going research vessels recorded puzzling data based on the magnetism of the ocean floor. It was determined that the rock of the ocean floor had alternating bands of embedded iron oxides that pointed north and south.

Although it is not completely understood, the Earth's magnetic field is thought to be created by convection of the liquid iron/nickel alloy that forms the Earth's outer core. The outer core is extremely hot (its temperature is thought to range from about 3000°C in the upper regions to about 6000°C in the lower region near where it meets the solid inner core) and convects like hot water in a tightly enclosed pan, under great pressure. The convection of liquid iron acts like a dynamo, creating the Earth's magnetic field. Like an ordinary bar magnet, the Earth's magnetic field is bipolar, with a North Magnetic Pole and a South Magnetic Pole.

It is believed that the earth's magnetism is created by slow movements in the liquid outer core, caused by the rotation of the earth. The generation of the earth's

For reasons that are not yet well understood, but are probably to do with instabilities in the convection currents in the outer core, the Earth's magnetic field flips back and

forth from time to time, when the magnetic poles reverse their position. Thus the magnetic field has two states: either normal polarity like that of the present, or reversed polarity. In times of normal polarity the North Magnetic Pole is located in the Arctic and the South Magnetic Pole in the Antarctic. During times of reversed polarity the North Magnetic Pole is located in the Antarctic, and the South Magnetic Pole in the Arctic. Today a compass is magnetized so that it points north towards the North Magnetic Pole, but when the magnetic poles reverse position the same compass would point south toward the North.

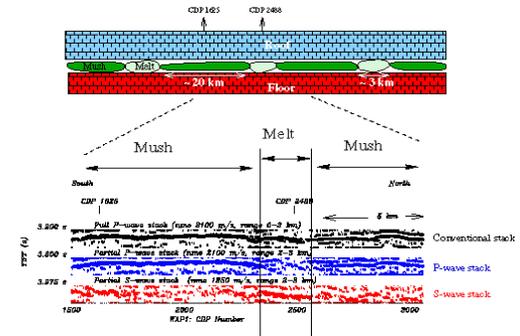
Magnetic Strip Anomalies

How magnetic stripe anomalies form? The iron contained in the rocks of the oceanic crust-gabbro, dolerite and basalt - can be magnetized. When the magma upwelling along mid-ocean ridges cools, the iron will take on the magnetic polarity of the Earth's magnetic field when the temperature of the cooling rock drops below about 730°C (known as the Curie temperature for iron). The magnetic polarity imprinted on the iron will be frozen in place in the new rock of the oceanic crust at the mid-ocean ridge.

At mid-ocean ridges new oceanic crust is being formed continually by upwelling of magma along the rift. The magma cools to form rock, taking on the magnetic polarity prevailing at the time. The new crust eventually splits apart, with the two sides moving away to either side of the rift to make room for fresh magma to rise up. Thus parallel bands of crust on either side of the mid-ocean ridge have the same magnetic polarity. When the Earth's magnetic field reverses its polarity, the rock being formed will take on the new polarity, and so as it splits and moves away from the ridge it will create new bands of crust on each side with the opposite polarity to their predecessors.

In this way, the ocean floor comes to consist of alternating bands (i.e. stripes!) of crust running parallel to the mid-ocean ridges, with every band having the opposite polarity to the bands on either side of it. Furthermore, the pattern of bands on one side of the mid-ocean ridge is exactly matched by the pattern on the other side. Thus the same pattern can be traced on either side of the ridge, often to a distance of several thousand kilometers! Sea-floor spreading, in turn, is a key element of plate tectonic theory.

Mid-ocean ridge magma chambers mapped by the seismic reflection data



Cartoon of along-axis segmentation of magma chamber beneath the southern East Pacific Rise from partial-aperture stacks of large-offset seismic reflection data.

Full waveform inversion (Collier and Singh, 1997) was performed on multi-channel seismic reflection data collected along the northern and southern East Pacific Rise to compute accurate velocity structure which confirmed the presence of a thin (<50 m thick) molten sill (Singh et al., 1998). Along axis variations of the molten state of the magma on a few-tens of kilometer scale were detected. These results help in understanding how melt is delivered from the mantle, the eruption history of mid-ocean ridges and the process of oceanic crustal accretion.

Some important new results from Central Indian Ridge, Carlsberg Ridge and Andaman Basin

South East Indian Ridge

A detailed study of magnetic and bathymetry was carried out in the Central Indian Basin revealed the presence of a new fracture zone at 75° 45'E trending N12°E (Kamesh Raju and Ramprasad, 1989). The differential offsets observed in the identified magnetic anomalies across the new fracture zone are explained in terms of the evolution of the triple junction. Kamesh Raju (1990) confirmed the presence of 73°E fracture zone. The study also gives an indication that the boundary marking the crust generated by the Central Indian Ridge and the Southeast Indian Ridge this region probably lies west of 71°E. Kamesh Raju (1993) observed several seamounts cluster along the inferred fracture zones at 73°E, 76°30'E and 79°E inferred fracture zones at 73°E, 76°30'E and 79°E and they represent smaller chains of a major hotspot trace. The prominent and subtle east-west trending bathymetry lineations across the 79°E fracture zone indicate strong and weak coupling at Ridge transform intersection (RTI), respectively during various stages of evolution (Kamesh Raju et al., 1993). The thermal

evolution model of fracture zone suggests the thickness of oceanic lithosphere is about 100Km.

Carlsberg Ridge

Analysis of the magnetic data leads to the identification of the Brunhes / Matuyama boundary (0.73 Ma) across the ridge axis and the absence of Jaramillo event (Ramana et al., 1993). The occurrence of large amplitude magnetic and gravity anomalies in association with the bathymetric deep in the northwest within the rift valley is suggested to be a zone of future segmentation of the ridge axis. A new transform fault appears to offset the trend of bathymetric and gravity contours in the northwestern part of the study area.

Central Indian Ridge

The Central Indian Ridge (CIR) segment is partitioned by a transform fault at about 7°45'S latitude, displacing the ridge axis in a right lateral sense. The spatial emplacement of the constructional volcanic ridges on either side of the ridge axis together with magnetic model studies suggest asymmetric spreading of ridge segment, which also is indicative of a waxing phase of magmatic activity during the recent past (Kamesh Raju et al, 1997). The well-developed rift valley with a poorly recognizable neovolcanic zone and the absence of a prominent MBA low suggests a waning phase of the magmatic activity. These observations suggest the predominance of tectonic extension during the present stage of evolution.

Andaman Backarc ridge

Rock samples from the rift valley and cratered seamounts show vent-like features and broken part of chimney structures together with pyrite clusters suggest the presence of evidence for hydrothermal activity along the SW-NE trending Andaman Backarc Ridge with two distinct segments of spreading (Rao et al, 1996). The studies of Kamesh Raju et al., (2004) revealed several morphotectonic features that divide the basin into a complex western part comprising arc-parallel seamount chains and N-S trending fault systems and a relatively smooth eastern part. A SW-NE trending spreading ridge bisects the basin with thin sediment cover over the SW segments while its NE segment has thick sediment cover and a well-maintained rift valley. It is suggested that the true seafloor spreading started about 4 Ma in the Andaman backarc basin, rather than the 11 Ma postulated previously. The basin has evolved as a consequence of extrusive tectonics that prompted extension and rifting along the plane joining the Sagaing and Semengko fault systems forming the deep Andaman backarc basin. A jump spreading centre during Late Oligocene, rifting and extension during Middle Miocene to Early Pliocene followed by the recent true seafloor spreading since last 4

Ma define the three-phase tectonic evolution of the Andaman backarc basin (Kamesh Raju, 2005). It is suggested that ridge propagation modulated the crust. A schematic evolutionary sequence of the Andaman backarc basin is presented.

The tectonic evolution of the Andaman basin with special reference to the formation of oceanic crust within the backarc basin encompassing the backarc spreading, suggests a phase of ridge propagation. Swath bathymetry data documented topographic fabric of the ridge propagation and reveal several morphotectonic features that divide the basin into a complex western part comprising arc-parallel seamount chains, N-S trending fault systems and a relatively smooth eastern part. The recent phase has experienced westward propagation of the spreading centre.

Distinctly different rupture patterns of December 2004 and March 2005 mega thrust earthquakes occurred in the Andaman-Sumatra region suggest strong influence of tectonic and structural elements (Kamesh Raju, 2007). The West Andaman Fault (WAF), which forms a lithospheric scale boundary together with other tectonic elements modulate the occurrence of large earthquakes and their rupture pattern. The active strikeslip motion along the WAF, presence of backarc spreading coupled with increased obliquity of subduction in the Andaman Sector reduce the probability of occurrence of major or great earthquakes north of 10°N.

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